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PLASMA INTERACTIONS WITH LARGE SPACECRAFT

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1. Introduction

Plasma interactions with large, high-power space structures have been shown to have an important influence on the operation of these systems. The importance of interactions of spacecraft with the environment was dramatically illustrated on the earliest shuttle flights, with the observation of shuttle glow and of high concentrations of particulates. Analysis and space experimentation have shown that environmental interaction effects on satellite performance grow nonlinearly with the size of the spacecraft and with power system voltages. The rapidly expanding role of satellite systems in civil sector communications and earth resources management, in the conduct of the Department of Defense mission and in NASA's plans for a space station and planetary missions of growing complexity, highlights the need to understand and model the space system plasma interactions and to develop techniques to mitigate systems-degrading interactions.

Future military systems to become operational in the 1990's require very large platforms, unprecedented memory and computational capability, enhanced power-generating systems, and must remain operational for decades. There is a quantitative change in the nature of the mechanical, electrical, thermal, and radiative interactions of these space systems with the environment. Space-Based Laser and Space-Based Relay Mirrors must be designed to minimize contamination effects on optics and mirror surface erosion. Planned SDI Systems and Space-Based Radar require orders of magnitude increases in power and must cope with enhanced plasma interactions which can cause unacceptable power losses. EVA required for spacecraft servicing on polar orbit flights must compensate for increased astronaut charging, particularly in the auroral zones. By the year 2000, the National Space Plane and the Space Station will become realities. The size and power requirements represent a real challenge to system developers. Designers of space systems contemplated for SDI must address all of the interactions under discussion.

2. Large-Body Space Plasma Interactions

A body moving through the space plasma at orbital speeds, approximately 8 km/sec, produces changes in the local environment and the local environment induces changes in the properties and performance of the vehicle. Some of the interactions of a satellite with the space environment are summarized in Figure 1. These interactions result in significant changes in the local environment properties and include enhancement of neutral and of ionized particle densities in the ram direction and rarefaction in the wake behind the spacecraft. Further, while ions and electrons are constrained by the Earth's magnetic field, neutral particles generated by the spacecraft are free to travel with the spacecraft until disturbed by collisional processes. The influence of the spacecraft on the environment can thus extend great distances. A brief discussion of some of the important large body interaction effects follows.

2.1 Ram-Related Effects

The first class of effects to be considered is related to the rapid (8 km/s) movement of spacecraft relative to the ambient neutral and plasma environment at low altitudes (H < 1000km). Two such effects will be considered here - glow and oxygen erosion. The presence of optical emission or glow above shuttle surfaces exposed to ram was observed on STS-3 by Banks et al. (1983) (see Figure 2 for an example). Mende et al. (1984) showed a clear dependence of the intensity of these faint visible emissions on the angle of attack. Glow had been previously observed on board the Atmospheric Explorer -C and -E spacecraft (see Yee and Abreu, 1983). Slanger (1983) suggested that the emission was related to the OH Meinel band system generated by the surface interactions with energetic oxygen atoms. Green (1984), on the other hand, proposed a chain of reactions resulting from dissociation of N_2 upon impact with the shuttle surface leading to the emission being the red N_2 first positive bands. Alternatively, Papadopoulis (1984) has suggested that physical mechanisms, namely beam plasma discharge and critical ionization phenomena, combine to produce the phenomena. Identification of the actual mechanism(s) awaits better spectral definition of the emissions.

Of particular interest to future space systems are the spectral content of the glow from IR to UV, the spatial extent of the glow, the variation with surface properties and other induced effects, and the potential degradation of optical measurements by its presence. Banks et al. (1983) estimated that the glow extended out about 10 cm from the surface. That distance may be variable dependent upon surface materials. Further, glow can be enhanced by the operation of thrusters and is altitude dependent. Thus, with a better understanding of the glow phenomena, materials selection or spacecraft and optical-bandwidth operations contraints may be able to mitigate the actual impacts on a given system.

Another ram-related effect at low altitude is the erosion of materials by neutral atomic oxygen. Because of the 8-km/s relative velocity, ambient oxygen atoms strike the ram surfaces with an energy of 5eV. This introduces a regime of gas surface chemistry about which little is known (see Arnold and Peplinski, 1985). In-flight studies by Visentine et al. (1985) have shown that the reaction between the environment and surfaces is to a first approximation not dependent on temperature, solar radiation, or electrically charged species. Reaction rates are material and incidence-angle dependent. In assessments of the effects to be seen by the NASA Space Station, Leger et al. (1985) indicated an enhanced susceptability of the materials used in solar power systems to oxygen erosion. While protective coatings are being selected, careful study is needed in order to identify practical candidates that fulfill both conductivity and oxygen erosion requirements in this orbital regime.

2.2 Wake-Related Effects

Just as the ram pressure causes interaction effects, similarly the lack of pressure or particles in the wake behind a large body has its own class of interactions. Figure 1 summarizes some of the interaction physics involved with both the ram and the wake regions. The supersonic motion of the body through the ionospheric plasma creates a shock wave in front and to the side and a large depleted volume behind the body. When the body size becomes very large comparable to Debye lengths or to ion gyro radii, the interaction effects relative to the filling in of the wake become more severe.

Measurements by Siskind et al. (1983) document nearly four orders-of-magnitude electron-density variations between the Shuttle ram and the wake. The lower limit of 10^2 electrons/cm^3 that they measured in the wake clearly results from instrument limitations. In fact, charged particle densities may go as low as 1/cm^3 in the deep wake (Shawhan, private communication, 1985). Densities in the ram may reach 10^7/cm^3 as indicated by saturation of the ion signal from the retarding potential analyser (SRPA) on STS-3 (Siskind et al. 1983). Thus, at least 7 orders of magnitude variation may be possible.

The shock structure from the ram flow and the strong gradients at the edge of the wake are obvious areas where turbulence could be expected. Siskind et al. (1983) and Raitt et al. (1983) found extreme plasma turbulence, especially when densities exceeded 10^5/cm^3. They conclude that turbulence occurred from ram effects and from enhancements from shuttle generated gases. Turbulence was also increased when the vehicle became negatively charged relative to the ionosphere.

The filling of the wake behind a large body moving supersonically or the expansion of a plasma into a rarified area has been studied by a number of people and reviewed by Samir et al. (1983). Multiple charged-particle populations result in polarization electric fields which control particle motion along with flow expansion in the collisionless case and diffusion in cases where collisions must be considered. From these processes the wake region becomes a source of electron heating and ion acceleration, preferentially of lighter ions and of minor constituents. Other processes involve plasma oscillations and instabilities, strong "jump" discontinuities in plasma parameters at the expansion front, and rarefaction wave propagation into the ambient plasma. These phenomena all depend on the ionic constituents and concentrations, ambient electron temperature and density gradients, and the size of the body relative to the Debye length.

2.3 Charging

Spacecraft charging results when insufficient thermal plasma can be collected by a surface to offset the impingement of intense fluxes of energetic charged particles. The surface will adjust its charge to repel enough of the energetic particles to maintain a zero net flow of current.

The discovery of charging in the low-density plasmas at geosynchronous orbit by DeForest (1972) and the subsequent recognition of charge-induced anomalies in spacecraft operations sparked numerous conferences and a satellite program, Spacecraft Charging at High Altitudes (SCATHA), to investigate the phenomena. A discussion and compendium of references on surface charging can be found in reviews by Garrett (1981) and Whipple (1981).

DMSP observations by Gussenhoven et al.(1985) established that the conditions necessary for charging to occur can also be found in auroral zones at low altitude (840 km) in polar orbit. They found that charging of over 100V occurred at the poleward edge of the region of discrete aurora in darkness when the thermal plasma density was less than $10^4/cm^3$ and a high integral number flux of electrons greater than 14 keV was present. These conditions are just as easily met at Shuttle altitudes in the Shuttle wake. In fact, the aforementioned lower thermal plasma densities should make this a common phenomenon in the nightside auroral regions.

Because of differing surface properties, spacecraft or objects in the wake can be expected to differentially charge or independently charge to different voltages. Large potential gradients over small distances may develop which can lead to arc discharges. These discharges may, in turn, release energy that damages electrical circuits or causes permanent damage to insulators.

The above discussions refer primarily to surface charging. A second charging problem arises in insulators when the charge becomes trapped below the surface (see Denig and Fredrickson, 1985). Bulk charging of insulators, often referred to as deep dielectric charging, grows to the point where breakdown channels are created. These may be temporary or permanent. Material properties' changes have been shown to occur in a charging environment which may lead to more subtle, anomalous behavior (Fennell et al., 1985).

2.4 Contamination

Early observations indicated that the Shuttle's local environment was controlled by the movement of the Shuttle through the ambient medium and by contaminant sources on the Shuttle. These sources, in the form of particulates (Carrignan and Miller, 1983; Grebowski et al., 1983; Narcisi et al., 1983) and gases (Carrignan and Miller, 1983; Barengolz et al., 1982; Maag et al., 1982) are generated by Reaction Control System (RCS) and Orbital Maneuvering System (OMS) engine firings, cabin gas leaks, water releases and outgassing of materials. Initial operational concerns over contamination focused on particulates scattering light into Shuttle-based optical detectors to produce false signals, and on gaseous contaminants condensing on thermal control and optical sensing surfaces to degrade their performance.

Recent observations, summarized by Green et al. (1986), suggest that the Shuttle may be immersed in a large gas cloud, made of atoms and molecules from various outgassing sources, whose shape is governed by the Shuttle's interaction with the ambient neutral atmosphere and space plasma environment. Engine firings enhance the contaminant cloud and may produce their own characteristic contaminant cloud or plume that has an associated engine firing light-flash (Weinberg, 1983) which illuminates the Shuttle and enhances the surface glow phenomena (Mende, 1984). Particulate contamination is also enhanced when RCS engine exhaust plumes impinge directly on Shuttle surfaces (Barengolz et al., 1982; Maag et al., 1982). All of these observations suggest a close coupling between the various contaminant sources which contribute to the formation of a multi-species gas cloud surrounding the Shuttle.

Some of the key experimental questions relative to the gas could include:

a. What is the absolute concentration of ions and neutrals in the cloud region and shuttle bay? What is their relationship to Shuttle activity?

b. What are the optical radiation characteristics of the cloud in the infrared, visible, and ultraviolet?

c. What is the spatial extent and temporal history of the cloud?

d. What is the intensity of the foreground luminescence of the Shuttle gas cloud at various wavelengths versus the intensity of backgrounds including the aurora, airglow, and stars?

e. Where do the particulates originate? What is their size, distribution, and time history?

Only when these questions have been satisfactorily answered can initial operational concerns over contamination be resolved through application of a Shuttle contamination specification to the broad class of Shuttle users.

The question of spacecraft contamination is perhaps more general than the composition of the local atmosphere (or gas cloud) which surrounds the space shuttle. Erosion of materials in the environment of the space shuttle has been documented in a number of experiments (Peters et al., 1983; Leger et al., 1984; Whittaker et al., 1985) and it leads to the natural question of the fate of the materials which are removed. A corollary question is the transport of materials from one place to another in this local atmosphere. For example, TQCM measurements on a number of missions (Scialdone et al., 1978; Triolo et al., 1984; Ehlers et al., 1984) indicate that materials are deposited on detectors. This transport must be correlated with the materials removed from the other surfaces. How this transportation occurs will play a crucial role in the assessment of contamination and its effects on shuttle operations. An ancillary question is whether the erosion of materials gives rise only to particulates or to particulates and gaseous contaminants. Laboratory experiments with electron and ion bombardment of surfaces show that ions and neutrals characteristic of the surface layer are emitted (e.g., Shapira and Friedenberg, 1980). In space, similar effects have been reported (e.g., Hanson et al., (1981) report observation of Na^+ and K^+ because of sputtering from satellite surfaces by ambient ions and neutrals). It is important to establish the extent of sputtering phenomena occurring in the local environment of the space shuttle, particularly at high latitudes. Species emitted in this fashion then become contaminants.

2.5 Radiation Hazards

The highly variable fluxes of energetic particles throughout the magnetosphere-ionosphere system represent a significant threat to space systems' survivability. Regions of particular concern are the earth's radiation belts extending from 1.1 to 7 RE in the magnetic equatorial plane and the high-latitude auroral zones (Fig. 3). During geomagnetic disturbances, energetic charged particles with energies up to 100 MeV are trapped along the earth's magnetic field lines. Particles of energies greater than 2 MeV cannot be shielded without significant cost and weight increases. An example of the effect of an energetic positive ion or cosmic ray upon a single microelectronic memory cell is depicted in Figure 4. The particle loses energy as it traverses the cell and ionization is created along its path. This in turn changes the operating potential of the device which can produce single event upsets or complete latchup. Deep dielectric charging can also occur as a result of satellite bombardment by energetic particles. There is potential buildup on the outer conductor of spacecraft cables. The high potential can eventually cause breakdown of cable insulation with subsequent discharge to cable conductors, and permanent damage results.

2.6 High-Voltage Induced Leakage to Space Plasmas

Exposed voltages on any part of a space system cause current to flow between the element and the ambient low-energy plasma environment. For example, current flow to a solar array terminal often can result in unacceptable power losses. At present almost all satellites use 28-volt supplies. In order to meet the needs of planned systems, such a Space-Based Radar or space station, much higher power must be generated. It is planned to use up to 1200 volts. The NASA Lewis PIX experiments have shown that the leakage current nonlinearly increases for high positive voltages and arcing occurs for high negative voltages (Purvis, 1983; Grier, 1983). These results are summarized in Table 1. The problems of operating at high voltages and currents are discussed in separate Workshop papers by Purvis and Stevens.

2.7 Multi-Body Charging and Polar Orbit EVA

A free flying subsatellite launched from the Shuttle (or space station) or an astronaut in EVA will be subject to the same environmental interactions as the parent orbiting vehicle but, because of size and surface material differences, will react differently. Potential differences can be built up between the free flying body and the vehicle. Such multi-body interactions must be understood, modeled and mitigated before spacecraft servicing can become a viable operational capability. The effects are greatest in the near wake of the main body where high potentials can develop due to loss of ions from the region (see section 2.3).

3.0 Plasma Interactions Control and Mitigations

Several efforts have been intiated by the Air Force Geophysics Laboratory in order to understand, quantify and mitigate against the hazards presented by space plasma interactions with large structures. Critical measurements will yield the data necessary to identify and establish mitigation techniques. These in turn will be transitioned to the space community to provide designers with important new design criteria and options.

3.1 Mitigating Against Radiation Hazards

The Air Force Geophysics Laboratory has established a spaceflight project SPACERAD for the space test of emerging microelectronic technologies while simultaneously measuring the space radiation environment. A 1989 launch is planned. The spaceflight performance of approximately 65 memory and logic devices including VHSIC technologies will be determined. The seventeen diagnostic instruments include particle detectors over the energy range from electron volts to 50 BeV, magnetic and electric field sensors, plasma wave analyzers and dosimeters. At the same time a microelectronic ground test program will be conducted with the goal of establishing ground test procedures for future technologies. Some experts, for example, consider that existing test procedures designed to assess performance in space are too severe. The consequence is that needed microelectronic capability is not available and in some cases results in over design of spacecraft shielding. The results of the particle, plasma, wave and field measurements on the SPACERAD satellite will be used to develop the first dynamic radiation belt models.

3.2 Quantification of Large Body Interactions and Technology Transitions

To quantize the effects of environmental interactions on technologies for future systems, the Interactions Measurement Program for the Shuttle (IMPS) has been established by the Air Force Geophysics Laboratory (Fig. 5). The purpose of IMPS is to develop synergistic sets (instrument complements) of engineering and scientific investigations that measure the interactions of the space plasma environment with representative large space structures, materials, equipment and technologies. The IMPS experimental payloads will be integrated into a Shuttle Pallet Satellite (SPAS) - a flight-tested carrier capable of free flight in close proximity with the Shuttle, allowing measurements of large-body space plasmas' interactions' effects on elements of planned systems. The diagnostic complement to be flown with the first IMPS/SPAS will form a space-qualified diagnostic facility resource for future Department of Defense (or NASA) technology systems.

The IMPS program represents a new approach to cost-effective spacecraft design for the large space structures and complex technologies of future space systems. Under this program a series of spacecraft flights will be conducted in which new technology components can be tested in-situ with proper diagnostics before commitment to final design of the complete system. The synergism of combining adequate diagnostics with components of systems for testing in-situ is critical to the effective transition of novel engineering concepts to future systems.

Timely results from IMPS-1 will be transitioned into criteria for new system designs to be implemented in the early nineties. It is planned that follow-on IMPS will address contamination and material degradation issues. On subsequent IMPS flights the basic diagnostics electromagnetic interface measurements will be combined with new engineering investigations and as required diagnostic instruments will be added to the basic core instruments.

As test elements grow in size, they reach a point where they can no longer be hosted by a spacecraft of the size of IMPS/SPAS. A transition must be made to a capability where the diagnostics are flown on a companion vehicle to that carrying the engineering experiment. Still larger structures may require interactions' measurements be made by a means of a highly maneuverable probe that can determine the interaction effects at various points over the surface. IMPS/SPAS can serve in both a host and a companion mode. An astronaut's maneuvering unit coupled with diagnostic tools is one way of satisfying a maneuverable probe capability requirement.

IMPS-1 is the beginning of a new capability to study complex, high-technology space systems. Large, high-powered systems of the future will interact with the plasma environment in many unforeseen ways. IMPS therefore offers a unique test facility out of which will come the understanding needed to affect future designs and to mitigate against adverse interactions. The benefits of this approach are a cost-effective, reliable, survivable spacecraft design and the early application of emerging technologies.

3.3 Spacecraft Charging Mitigation

Plasma experiments conducted on the Air Force SCATHA satellite showed that emission of a neutral plasma from a spacecraft in geosynchronous orbit could act as a clamp electrically connecting the spacecraft to the background plasma and thus prevent buildup of hazardous charging levels or catastrophic discharging. A device that can detect the onset of charging and turn on a plasma source is an effective spacecraft charge control and mitigation tool. Such an instrument is being developed by AFGL for geosynchronous orbiting satellites. The charge control system uses several techniques to detect charging and a rapid turn-on plasma source to automatically control spacecraft potentials over the satellite's lifetime (Fig. 6).

A similar device would also be useful for control of the potential of structures in low-earth polar orbit. By using several plasma sources at strategic points on large space platforms, hazardous differential potentials created by the interaction of auroral fluxes with the wake region or by on-board particle accelerations could be eliminated.

4.0 Summary

Space is playing a rapidly expanding role in the conduct of the Air Force mission. Larger, more complex, high-power space platforms are planned and military astronauts will provide a new capability in spacecraft servicing. Interactions of operational satellites with the environment have been shown to degrade space sensors and electronics and to constrain systems operations. The environmental interaction effects grow nonlinearly with increasing size and power. Quantification of the interactions and development of mitigation techniques for systems-limiting interactions is essential to the success of future Air Force space operations.

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SOLAR ARRAY OPERATING VOLTAGE VS PHYSICAL PHENOMENA

VOLTAGE LEVEL	PHYSICAL PHENOMENA
< 50V	STATE-OF-THE-ART
100-300V	PLASMA LEAKAGE LOSS >1%
200-500V	LEO PLASMA DISCHARGES
400-700V	PARTIAL-DISCHARGE INCEPTION IN SUBSTRATE
500-1200V	PUNCH-THROUGH AT SUBSTRATE IMPERFECTIONS

TABLE 1

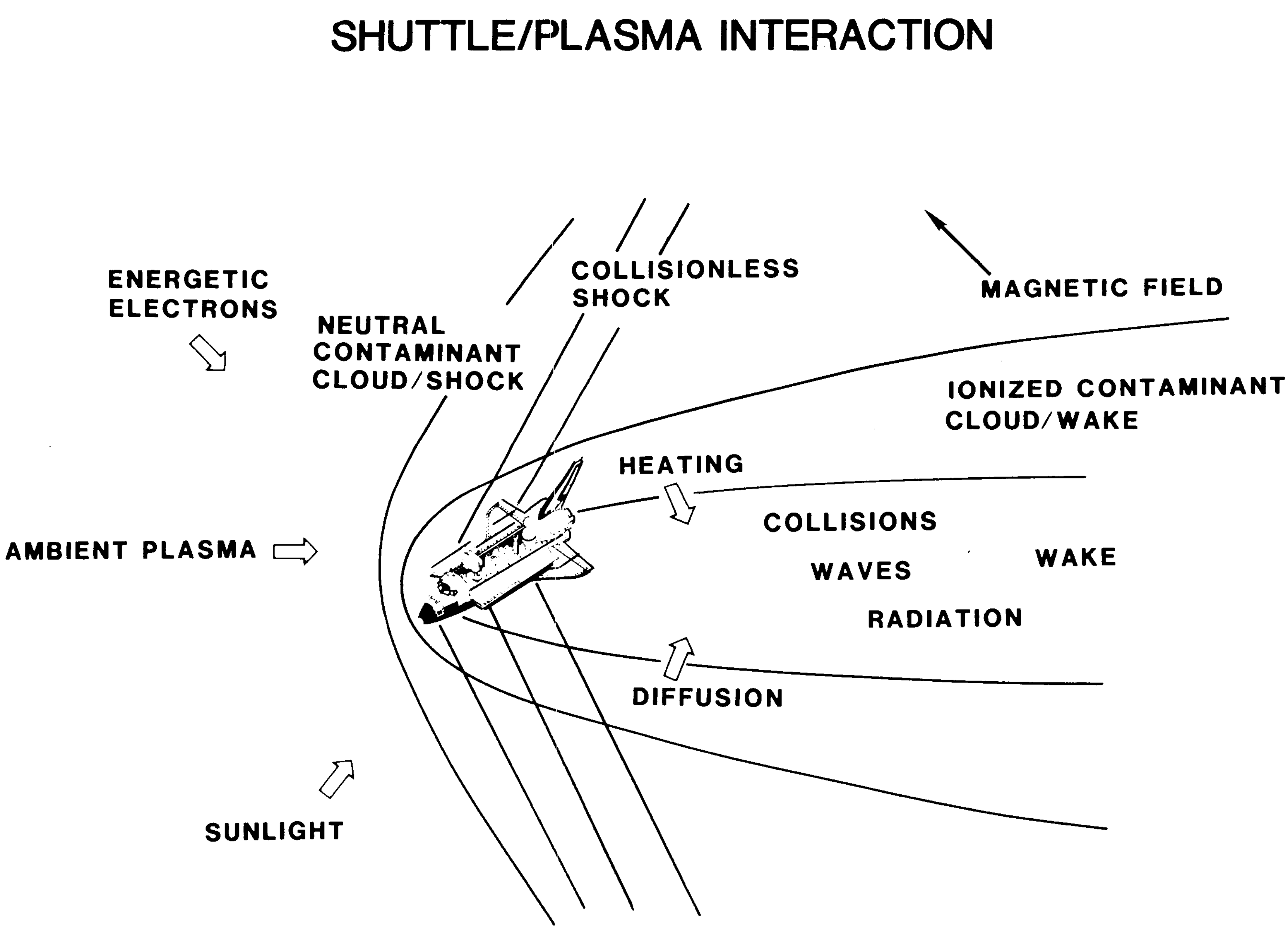

Figure 1. Illustration of impact of environment on a large space structure in low earth orbit.

Figure 2. Illustration of optical emissions from the Shuttle in the ram direction.

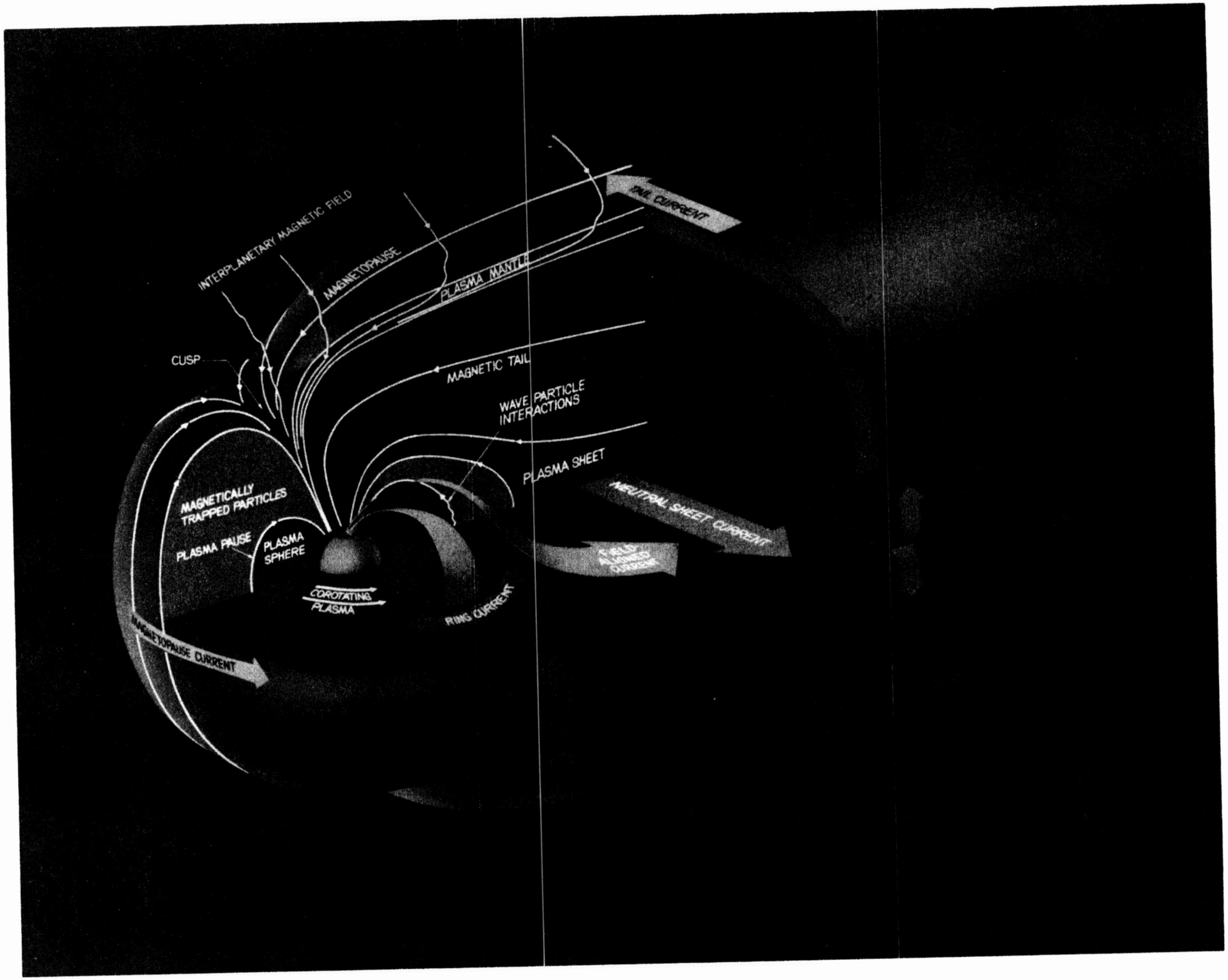

Figure 3. Throughout the magnetosphere-ionosphere highly variable fluxes of charged particles interact with orbiting spacecraft. The regions of greatest interest include the earth's radiation belts and the auroral zones.

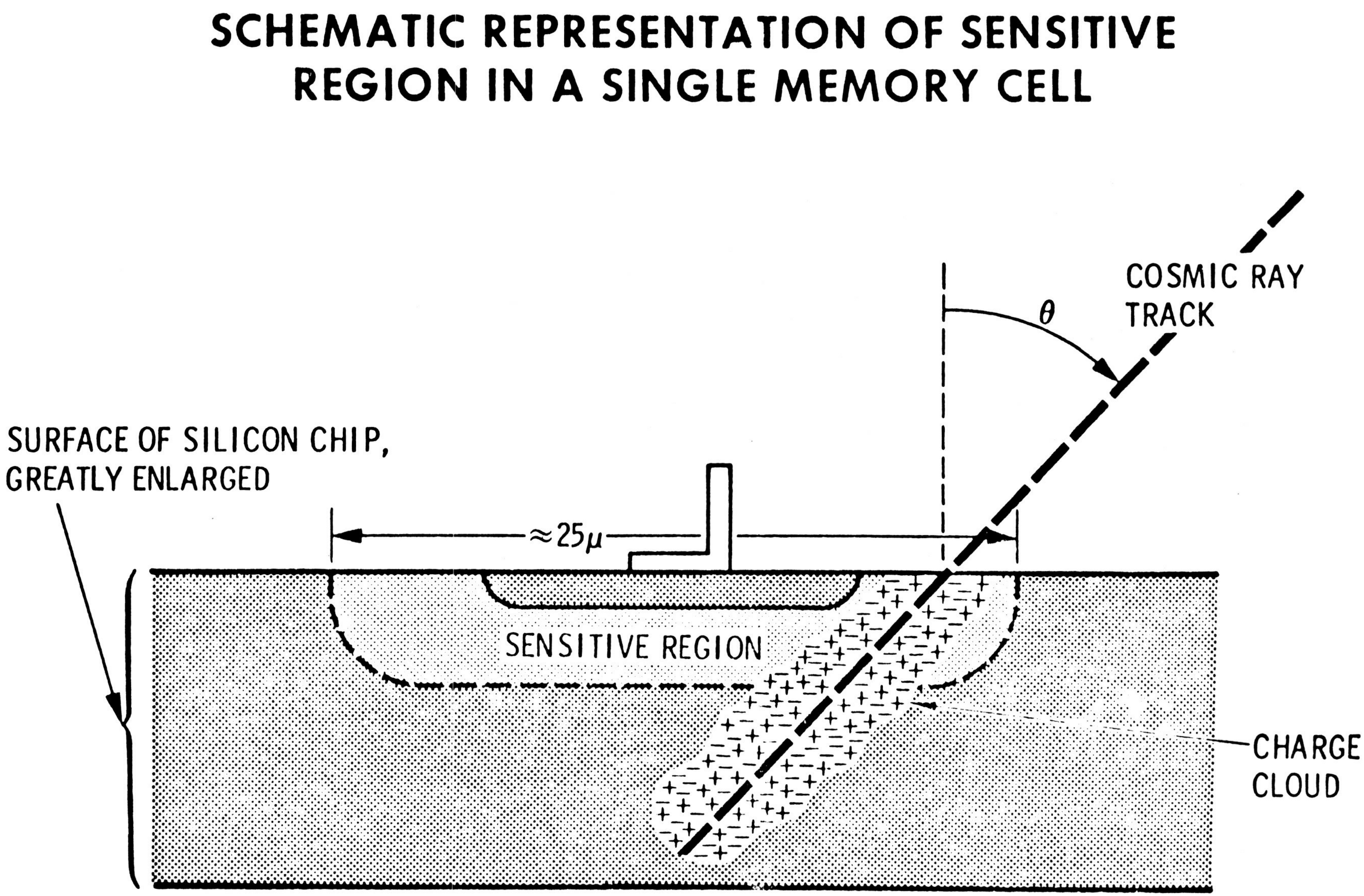

Figure 4. Depiction of the effects of energetic-particle traversal on a single memory cell.

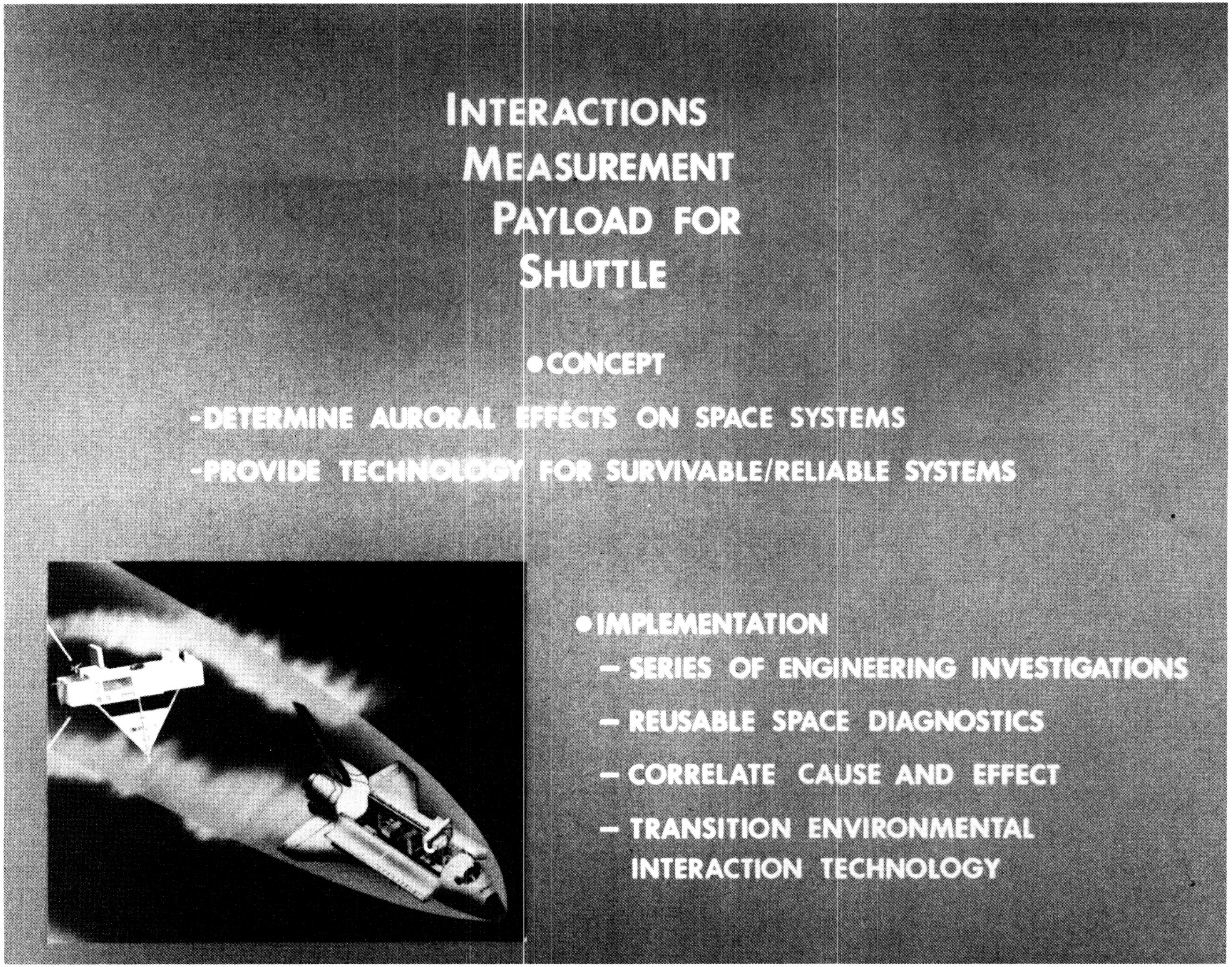

Figure 5. Interactions Measurements Program Satellite (IMPS) concept.

CHARGE CONTROL SYSTEM

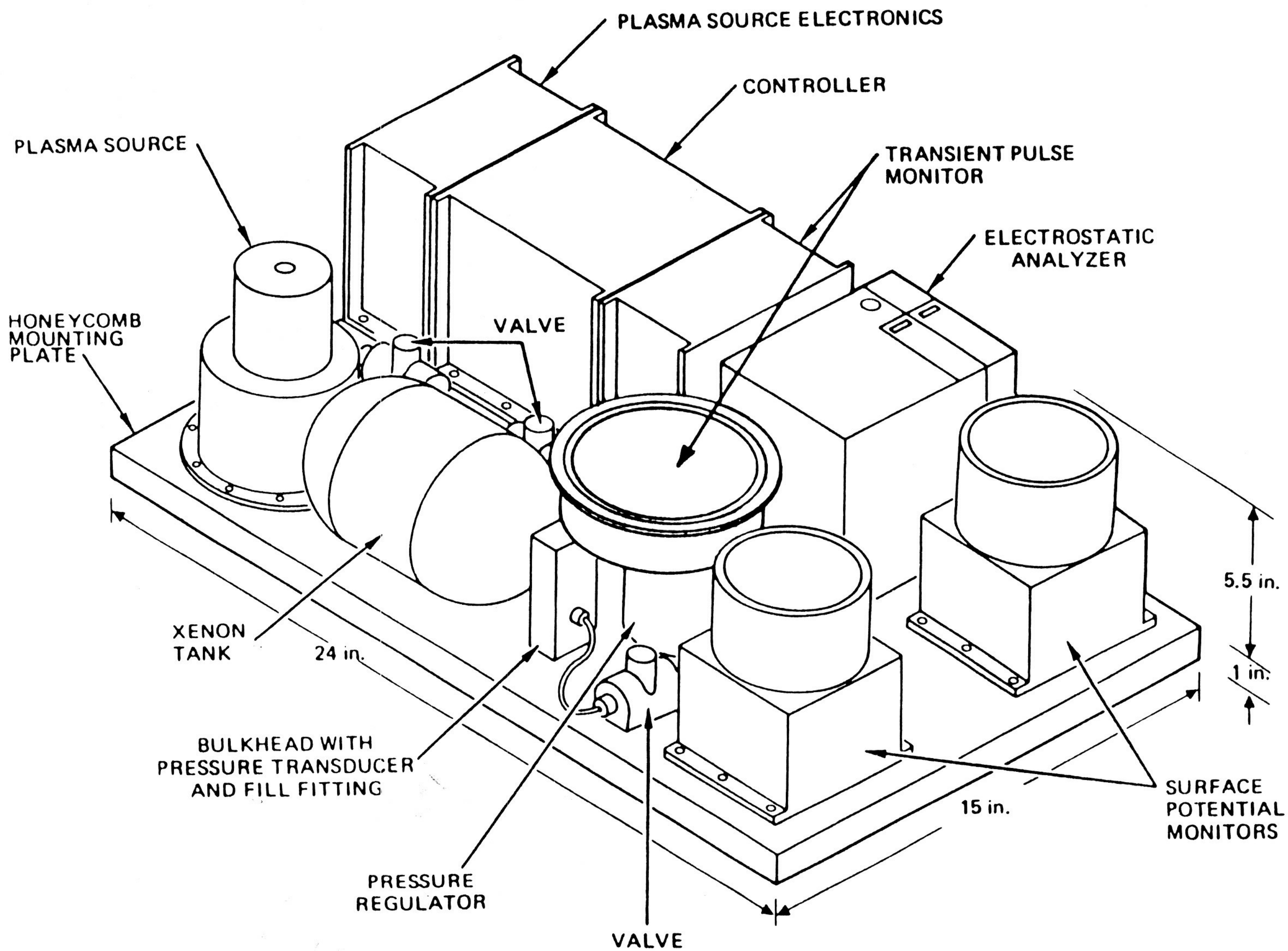

Figure 6. Block diagram of automatic charge control system.